2. Station opening and purchase policy,
3. Waiting time for stations with different locations and gasoline prices,
4. Station pricing policies, and
5. Sales data on average purchaser and self-service.

For public policy and station policies:

1. Minimum-maximum purchase,
2. Regular customers only,
3. Even-odd or other rationing,
4. Incentives for carpooling,
5. Improved transit service or other alternative service, and
6. Forced station closing (e.g., on weekends).

These data would be used to calibrate models of gasoline consumption and purchase behavior to address the research differences outlined above. These models would be used for evaluation of the costs and benefits of alternative queue-management and demand-management techniques. Particularly interesting would be evaluation of various contingency plans for changing transit service and increasing automobile occupancy. As indicated in these research papers, the costs of queueing could amount to billions of dollars nationwide. The value of such research, therefore, should be considered in light of these immense costs.

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Direct Energy Accounts for Urban Transportation Planning

B.N. JANSON, M. FERRIS, D.E. BOYCE, AND R.W. EASH

Methods for computing accounts of direct energy consumption by urban person travel are described. These accounts are compiled by mode, trip purpose, time of day, and origin-destination pair and are designed to be compatible with the existing transportation planning software and data sets. For automobile trips, a program is used to trace equilibrium assignment paths and calculate zone-to-zone fuel consumption based on link speeds and distances. A similar program for public transit modes calculates zone-to-zone energy consumption based on modal vehicle kilometers per person trip along each minimum impedance path. The final accounts are separate matrices of zone-to-zone energy flows for both public and private modes that can be summarized in tables or displayed graphically. Results from a case study of the Chicago metropolitan area are briefly presented.

A number of plans have been proposed to reduce the energy consumed by urban transportation. These include both contingency plans for short-term shortages of petroleum (1) and long-term plans that require major capital investment and reorganization of land use (2,3). Yet these plans remain controversial because their evaluation has been limited. Often the analyses rely on misleading or inconclusive statistics of modal energy use, or results from one metropolitan area are assumed to be correct for another, quite different, urban region.

Energy planning for urban transportation remains largely separate from the institutionalized urban transportation planning process that has evolved over the last two decades. Therefore, an accepted methodology for conducting urban transportation energy analyses compatible with this planning process does not exist. There are no state-of-the-art procedures from which the analyst may produce an energy evaluation of regional transportation plans or corridor modal alternatives. Evaluation of transportation investments is greatly hampered by the lack of detailed procedures for energy analyses that use the transportation models and data sets available to a metropolitan planning organization.

The objective of the project discussed in this paper is to contribute to the needs cited above by (a) designing procedures for computing urban transportation energy accounts, (b) developing computer programs for these procedures that are compatible with the urban transportation planning models and data sets, and (c) completing a trial application of these procedures in a case study. This paper is primarily concerned with the first two of these objectives; however, a summary of results from a case study of the Chicago metropolitan area is also presented.

OVERVIEW OF THE ENERGY ACCOUNTING PROCEDURES

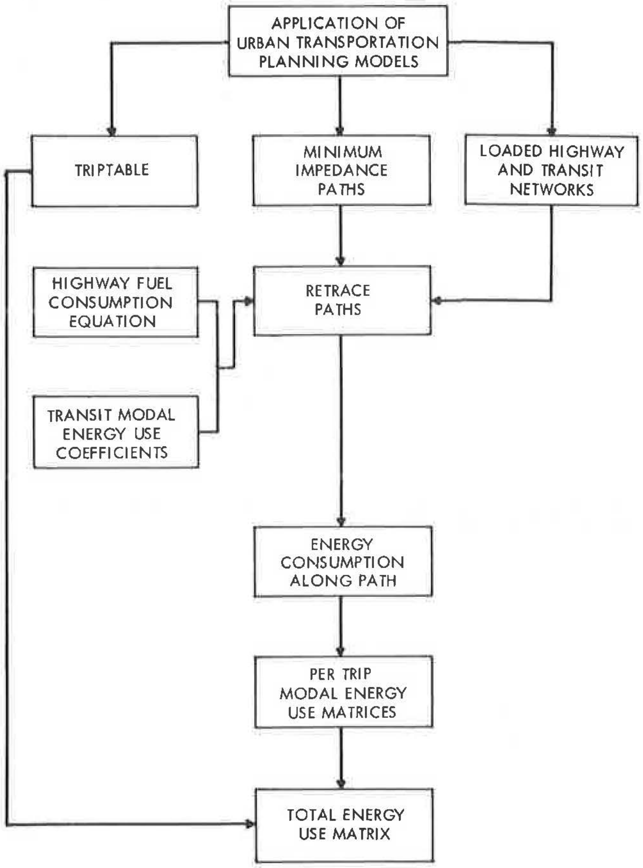
A general flowchart of the energy accounting procedures is shown in Figure 1. Three data files are required as inputs:

1. A loaded network that contains a description of the highway or public transportation network plus the estimated traffic or patronage,
2. A zone-to-zone trip table, and
3. A path or tree file that contains the minimum impedance routes between zones.

These files would usually be required or produced in any application of the urban transportation planning sequence.

Energy consumption is computed for origin-destination pairs by tracing the paths that result from using trip assignment models. First, the minimum impedance routes between zones in the highway and transit networks are read from the tree files. Fuel consumption for each highway path is calculated directly during the tracing procedure by using fuel-consumption coefficients for travel time and distance. For public transit modes, the path-tracing

Figure 1. General procedure for calculating energy-use matrices.



procedure calculates matrices of zone-to-zone modal vehicle kilometers per person trip. Energy consumption per person trip is then calculated by using values of modal energy consumption per vehicle kilometer. If the transit system includes electrically powered heavy rail, then a matrix separate from diesel-powered rail can be retained. The resulting files are matrices of modal energy consumption for the study area where each i-to-j cell in a matrix contains the modal energy per person trip between two zones. Energy consumption for all trips is calculated by multiplying these energy-per-trip matrices by the highway or transit trip table.

The structure of the energy accounts is shown below.

1. Mode
   a. Private automobile
      i. Driver
      ii. Passenger
      iii. Automobile-only trip
      iv. Transit access
   b. Public transportation
      i. Bus
         (a) Rail access
         (b) Local
         (c) Express
      ii. Rail rapid transit
      iii. Commuter rail
         (a) Electric
         (b) Diesel
2. Trip purpose
   a. Home-to-work
   b. Work-to-home
   c. Nonwork
3. Time of day
   a. 24-h weekday
   b. Morning and evening peak period
   c. Off-peak period
4. Origin and destination
   a. Analysis zones
   b. Districts
   c. Radial corridors
   d. Circumferential rings

These categories reflect the objectives of the study, the availability and disaggregation of data, and the types of transportation provided in the study region. In our study of the Chicago metropolitan area, separate accounts are computed for automobiles (including taxis) and public transit modes. For transit trips that use more than one mode (including access by automobile), energy consumption for each leg of the trip is allocated to the proper modal account. The accounts can also be compiled by trip purpose and time of day by using only the relevant portion of the highway and transit trip tables. The energy accounting procedures discussed in this paper deal only with direct energy consumption (i.e., the fuel or electricity consumed for vehicle propulsion and appurtenances). Methods for computing the indirect energy required for construction and maintenance of transportation vehicles and infrastructure are part of the accounting procedures developed for this study but are not discussed in this paper.

CONSTRUCTION OF THE ACCOUNTS

The basic approach to constructing these accounts is to use urban transportation trip-assignment models to compute person kilometers and vehicle kilometers of travel by the categories shown above. Detailed rates of energy consumption per vehicle kilometer by vehicle type (automobile, bus, or rail) are applied to convert vehicle kilometers of travel into units of energy consumed. Link speeds that result from equilibrium assignment are also used to compute automobile fuel consumption.

Highway Assignment

The highway trip table for the Chicago standard consolidated area (SCA) was developed from the 1970 census urban transportation planning package (4) data file of home-to-work trips, a home-interview survey conducted by the Chicago Area Transportation Study (CATS) in 1970, and a 1970 CATS commercial vehicle survey. The census file is a 15 percent sample of work trips, and the CATS home interview is a 1 percent sample of all trips. The combined trip table is factored from 1970 to 1975 by using changes in land use during this period. The trip table assigned to the network is the 2-h morning peak-period matrix of automobile, taxi, and commercial truck trips. However, the energy accounts for person travel that are calculated from the assignment do not include the energy consumed by truck trips.

The coded highway network for the Chicago SCA includes approximately 40 000 links and 15 000 nodes. A highway trip table is assigned to this network by using an equilibrium assignment algorithm (5) that was adapted for use with the Federal Highway Administration (FHWA) PLANPAC transportation planning software (6). Equilibrium assignment allocates trips to alternative paths such that, for each pair of zones, all used paths have equal travel cost and no unused path has a lower travel cost. These are known as Wardrop's equilibrium conditions (7). Each iteration of the algorithm converges toward equilibrium by combining the current all-or-nothing assignment with the previous combined assignment. Because the Chicago highway network is very large, only five iterations of the algorithm are performed. However, unlike the FHWA iterative assignment, each iteration of equilibrium assignment is guaranteed to improve the solution.

Highway Path Averaging

The procedure used to calculate fuel consumption for automobile trips is to first calculate the amount of fuel consumed by an average car on each link of the highway network. Then, as each zone-to-zone path is retraced, fuel consumption for each link along the path is summed. Because equilibrium assignment improves the estimation of zone-to-zone travel times and distances, it provides a sounder basis for the calculation of automobile fuel consumption than does the use of one all-or-nothing assignment. On a congested highway network, on which trips use several alternative paths, travel distance and fuel consumption are likely to be different for each path used. For this reason, the following procedure is used to calculate average zone-to-zone travel distance or fuel consumption that corresponds to an equilibrium assignment.

By using standard notation for equilibrium assignment, λ_n equals the fraction of the nth all-or-nothing assignment that is combined with $(1-\lambda_n)$ of the previous combined assignment. Each all-or-nothing assignment has a matrix of minimum path distances (m_{ij}). Once the value of λ_n is determined, it can be used to determine the average distance from zone i to zone j for the current nth solution $(d_{ij,n})$:

$$d_{ij,n} = (1 - \lambda_n)\, d_{ij,n-1} + (\lambda_n)\, m_{ij,n} \qquad (1)$$

Or, more generally

$$d_{ij,n} = (\lambda_n)\, m_{ij,n} + (1 - \lambda_n)(\lambda_{n-1})\, m_{ij,n-1} + \ldots + (1 - \lambda_n)(1 - \lambda_{n-1})(1 - \lambda_{n-2}) \ldots (1 - \lambda_1)\, m_{ij,0} \qquad (2)$$

The average travel distance from zone i to zone j is a weighted average of the travel distances along the minimum cost paths from i to j, where the λ's form the appropriate weights. Average zone-to-zone fuel consumption is computed in the same manner. In contrast, the travel times that are used to compute fuel consumption are those that result from the final set of combined link loadings.

Highway Path Tracing

Since PLANPAC does not compute zone-to-zone travel time, distance, or fuel consumption in the manner prescribed above, a separate program must be used to read and trace the paths from each all-or-nothing assignment. For this purpose, a program called CHPSUM is used to trace FHWA highway paths in an efficient manner. CHPSUM reads link records from the historical record network file and stores the distance and travel time for each link. It also computes the amount of fuel consumed by the average car for each link based on link type, distance, and speed. Then CHPSUM sums travel time, distance, and fuel consumption while each zone-to-zone path is traced in the reverse direction.

Note that travel time, distance, and fuel consumption for each link are stored only once prior to the tracing of all trees. Also, each link only needs to be traced a single time for all paths from a single origin because of the branching structure of a minimum-path tree. Otherwise, the tracing procedure would repeat itself over common segments of paths from the origin zone to the intersection node where these paths diverge. Avoidance of redundant calculations in the tracing procedure greatly reduces computer time needed to process trees for a large network, particularly since this is necessary for each set of assignment paths.

Each execution of CHPSUM produces matrices of zone-to-zone travel times, distances, and fuel consumption. Figure 2 displays the sequence of these calculations. These matrices correspond to distinct all-or-nothing assignments and must be averaged together in the manner described above. These weighted matrices are next multiplied by the original trip table and aggregated into district-to-district flows. Aggregation of the zonal calculations at this stage avoids the gross assumptions of calculations that begin with district averages of trip distance and speed.

Fuel Consumption as a Function of Speed

CHPSUM was originally designed to sum travel time and distance over each path by link type. However, travel time per unit distance (i.e., the inverse of speed) has been found by General Motors Research Laboratories (GMRL) (8) to be the single-most-significant variable that affects fuel consumption of a given vehicle in urban traffic. In a subsequent study by Chang and others (9), data were collected by GMRL employees who drove 1975-model-year vehicles with fully warmed engines on arterial streets in the Detroit metropolitan area. Travel time, distance, and fuel consumption were recorded each time the vehicle came to a full stop. The following linear equation was calibrated for each vehicle type for which data were collected:

$$R = k_0 + k_1 (1/S) \qquad (3)$$

where

R = fuel consumption rate (L/km),
S = speed (km/h),
k_0 = liters per kilometer, and
k_1 = liters per hour.

The resulting fuel-consumption equations are shown in Figure 3 for a subcompact, compact, and standard-size automobile. The dashed lines are shown for speeds between 24 and 56 km/h (15 and 35 mph) because the majority of GMRL's data observations fell within this range. GMRL did not perform separate tests for freeway driving. However, the Urban Transportation Planning System (UTPS) Characteristics of Urban Transportation Systems (10) contains fuel consumption coefficients for arterial and freeway driving for the three basic vehicle types listed above. Freeway driving is characterized by higher and relatively constant speeds over longer distances. The plots of these coefficients are also shown in Figure 3.

Although the manual states that these coefficients represent 1973-model-year vehicles, there is no clear explanation for the difference between the UTPS and GMRL values for arterial streets. It is difficult to evaluate contradictory data without additional information. We assume that the GMRL coefficients are more reliable since they resulted from well-documented experimental procedures. The UTPS values for freeway driving are similar to those reported by Claffey (11), despite the fact that Claffey used much older vehicles. In this study, the GMRL arterial coefficients are used for all links that have assignment speeds less than 40 km/h (25 mph) regardless of the designated link type, and the GMRL coefficient for 24 km/h (15 mph) is used for all links that have speeds less than 24 km/h. The UTPS freeway coefficients are used for

Figure 2. Direct energy calculations for automobile trips.

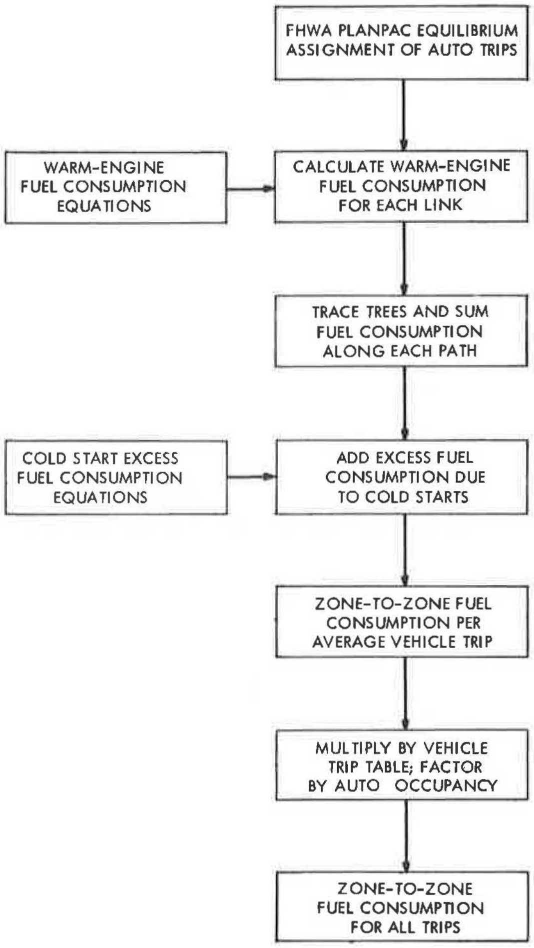
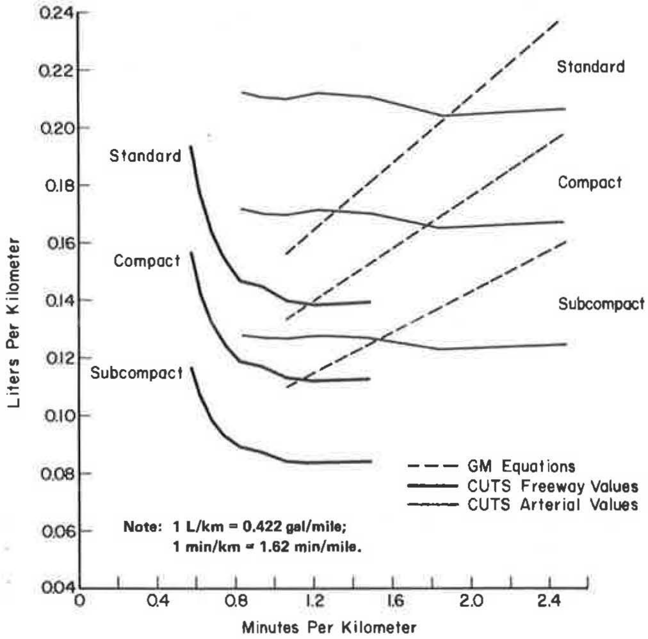
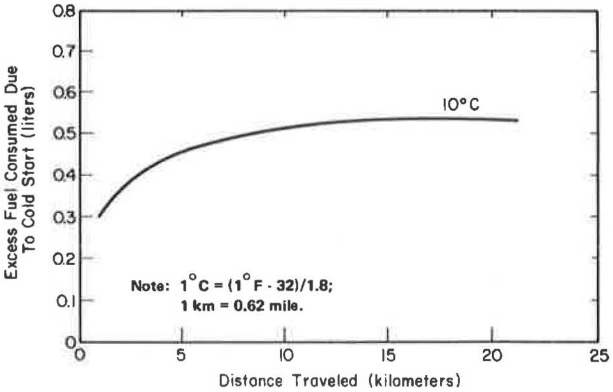


Figure 3. Warm-engine fuel-consumption coefficients for automobiles.



Note: 1 L/km = 0.422 gal/mile; 1 min/km = 1.62 min/mile.

Figure 4. Cold-start fuel-consumption coefficients for automobiles.



Note: 1°C = (1°F - 32)/1.8; 1 km = 0.62 mile.

all links that have speeds in excess of 64 km/h (40 mph). The link type is used to select the fuel-consumption rate for all links that have speeds between 40 and 64 km/h, and the rate for arterial links that have speeds greater than 56 km/h (35 mph) is assumed equal to the GMRL rate for 56 km/h. Although the UTPS values are for the 1973 model year, a two-year difference from the GMRL cars is assumed to be negligible.

When multiplied by the distance of a link, Equation 3 becomes

$$F_a = k_0 D_a + k_1 T_a \qquad (4)$$

where

F_a = fuel consumed on link a (L),
D_a = distance of link a (km), and
T_a = travel time on link a (min).

Values for the coefficients k_0 and k_1 are input to CHPSUM for each 8-km/h (5-mph) speed range from 0 to 160 km/h (0 to 100 mph). Thus, Equation 4, approximated by linear segments, is used to estimate the amount of fuel consumed per vehicle on each link, given link distance and travel time from the assignment. One may question whether travel times from the assignment are proper to use with coefficients based on data collected at actual driving speeds. Although equilibrium assignment may distribute traffic among links in a manner that approximates actual counts, an extensive validation between assignment times and survey times has not yet been completed by CATS.

Fuel Consumption Due to Cold Starts

A cold engine consumes fuel less efficiently than a warm engine. Because Equation 3 assumes a fully warmed engine, additional fuel consumption must be accounted for during the initial portion of each trip. Chang and others (9) estimated the curve shown in Figure 4 from tests performed by using a 1975 standard-size automobile at 10°C (50°F) ambient air temperature. Since cold-start curves for smaller cars were not available, this study uses 80 percent of the standard car values for compact cars and 60 percent of the standard car values for subcompact cars. These are the percentage differences between the UTPS arterial values in Figure 3. These curves represent fuel consumption in excess of that predicted by Equation 4 as a cumulative function over distance that ceases to increase beyond roughly 16 km (10 miles) of driving. Thus, Equation 4 is still applied to all links along the path.

Fuel-Consumption Coefficients for the Average Car

Numerous assumptions are necessary to derive fuel-consumption coefficients that represent the proper mix of vehicles by age and type for a specific year and region. First, although there are hundreds of different car models, this study assumes that an aggregation of cars according to three basic sizes is sufficient for estimation of average fuel-consumption coefficients for the Chicago region's vehicle fleet. The UTPS manual estimates the national mix of automobiles in 1973 to be 12 percent subcompact, 30 percent compact, and 58 percent standard-size vehicles (10). Although the vehicle fleet for a region may differ from that of the nation, specific data on vehicle mix for a particular region are very difficult to obtain. Thus, coefficients for the average car are derived in this study by combining the warm-engine and cold-start curves according to these percentages. Because these composite coefficients represent a 1973 (or 1975) vehicle, the calculations that result must be adjusted for the mix of vehicle ages in the operating fleet. Murrell and others (12) estimate that the average fuel efficiency of new cars sold nationally in 1975 was 36.7 km/L (15.6 miles/gal), but only 32.2 km/L (13.7 miles/gal) for the nationally operating fleet. Thus, actual fuel consumption in 1975 might be as much as 15 percent greater than estimates that assume the same model year for all cars in the study region. Clearly, the estimation of fuel-consumption coefficients for the average car in a given year requires a great deal of refinement that is only possible with more complete data.

Transit Assignment

The transit trip table for the Chicago SCA was developed from the same data files in substantially the same manner as was the highway trip table. One trip table that contained all users of transit in the 2-h morning peak period was assigned to the transit network. CATS codes all transit service for the Chicago region as one network that includes walk and automobile access links. CATS uses the UTPS ULOAD all-or-nothing transit assignment (13), which assigns trips to minimum impedance paths that include access and egress.

Transit Path Tracing

Details of the direct energy calculations for automobile trips have been discussed above. The procedures used to calculate direct energy consumption for transit trips maintain this same approach, except that transit energy consumption is assumed to be directly proportional to vehicle kilometers of travel. However, calculation of vehicle kilometers of travel per person trip between two zones is not a simple task because trips may use several different modes that have constantly changing vehicle occupancies.

ULOAD does not report zone-to-zone vehicle kilometers of travel per person trip; therefore, a path-tracing program called CTPSUM, which follows the same tracing logic as CHPSUM, was designed and used to perform these calculations. Whereas CHPSUM first calculates the average fuel consumption per vehicle trip on each link, CTPSUM calculates vehicle kilometers per person trip for each transit link. This is done by multiplying each link length by the frequency of vehicles and dividing by passenger volume. The number of vehicles per train and the length and time of day of the assignment period are taken into account when the number of vehicles that serve each link over the assignment period is computed. CTPSUM then proceeds to retrace the transit paths while summing both travel distance and vehicle kilometers per person trip by mode along each path. Since only one all-or-nothing assignment is performed, the tracing program is executed only a single time and no averaging is needed for alternative paths.

Calculation of Direct Energy from Vehicle Kilometers per Person Trip

Since a very limited number of access links are coded into a transit network, the access portions of transit trips require additional calculations. For this purpose, two separate transit trip tables are prepared: (a) transit-only trips and (b) transit trips that use automobile access to rail rapid transit or commuter rail. The transit-only trip table includes all trips that either walk to transit (rail or bus) or use access bus to a rail transit mode. The automobile-access trip table includes both automobile-driver and automobile-passenger trips. These access-mode trip tables are calculated from district access-mode factors computed from the CATS 1970 home interview survey. A matrix of zone-to-zone automobile-access distances is produced by taking the average distance by car to the closest rail rapid transit or commuter rail station. Whether to use distance to the rapid transit or to the commuter rail station is determined by the first rail mode of each assignment path. These automobile-access distances are converted into a matrix of zone-to-zone automobile vehicle kilometers per person trip by using zonal ratios of automobile-driver to automobile-passenger trips. In contrast, a matrix of zone-to-zone access-bus vehicle kilometers per person trip is output directly by CTPSUM.

A list of the transit matrices discussed thus far helps to explain the final calculations shown schematically in Figure 5:

1. Transit-only trips,
2. Transit trips that use automobile access to a rail mode,
3. Automobile-access vehicle kilometers per person trip,
4. Access-bus vehicle kilometers per person trip,
5. Bus (excluding access) vehicle kilometers per person trip,
6. Rail rapid transit vehicle kilometers per person trip, and
7. Commuter rail vehicle kilometers per person trip.

Matrix 1 times matrix 4 equals zone-to-zone vehicle kilometers of access-bus travel. (This is not the matrix algebra form of matrix multiplication but just a simple cell-by-cell multiplication.) Paths that use walk links to rail transit or do not use rail transit at all register as zeros in matrix 4 and thus do not contribute to access-bus kilometers. Matrix 2 times matrix 3 equals zone-to-zone vehicle kilometers of automobile travel for all transit trips that use automobile access to a rail mode. Finally, both the transit-only and the automobile-access trip tables (matrices 1 and 2) are multiplied by matrices 5, 6, and 7 to yield total vehicle kilometers of travel by each nonaccess mode.

To calculate direct energy consumption, the five matrices just described must be multiplied by coefficients of direct energy per vehicle kilometer for each mode. Average coefficients such as these tend to vary widely between cities because of age and operating differences (14,15). Based on operating

Figure 5. Direct energy calculations for transit trips.

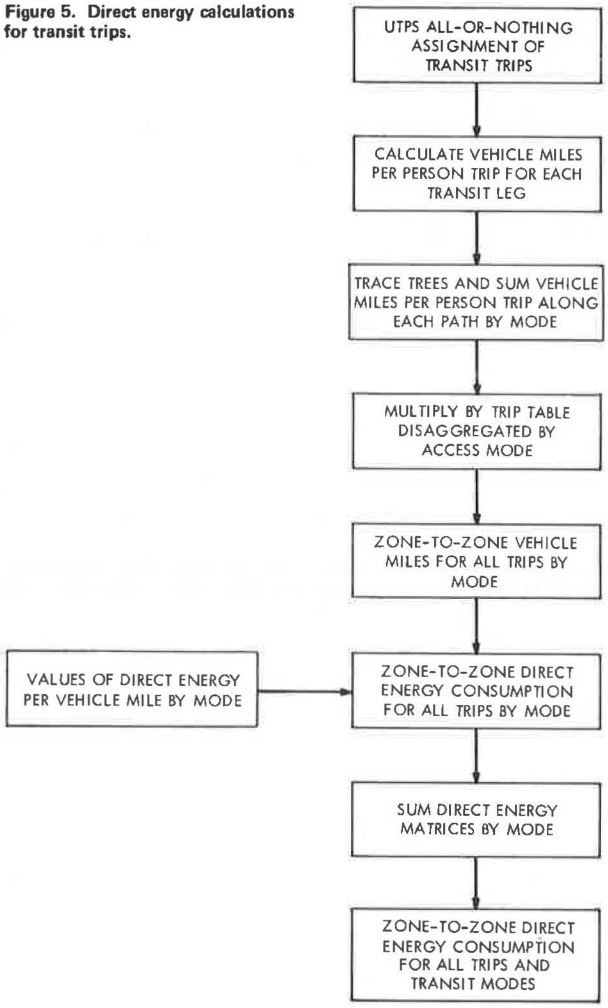


Table 1. Summary of direct energy accounts for Chicago SCA morning peak period.

Statistic	Private Travel	Public Travel
Direct energy (MJ)	177 300 000	9 910 000
Person trips	2 965 369	511 751
Person kilometers	33 967 381	7 754 486
Average trip length (km)	11.45	15.15
Megajoules per person trip	59.79	19.36
Megajoules per person kilometer	5.22	1.28
Person air kilometers	28 401 301	7 138 409
Average trip length (air-km)	9.58	13.95
Megajoules per person air-kilometer	6.24	1.39
Petroleum energy (MJ)	177 300 000	6 250 000
Electrical energy (MJ)	0	3 660 000

Note: 1 MJ = 947.8 Btu; 1 km = 0.621 mile.

data for the Chicago region, the estimates of direct energy per revenue vehicle kilometer used in this study are as follows:

Urban bus = 27.54 MJ/km (42 000 Btu/mile)
Rail rapid transit = 37.37 MJ/km (57 000 Btu/mile)
Commuter rail (diesel) = 68.18 MJ/km (115 000 Btu/mile)
Commuter rail (electric) = 86.54 MJ/km (132 000 Btu/mile)

For automobile access, this study assumes the 40-km/h (25-mph) fuel-consumption rate estimated by GMRL for arterial roads and the UTPS vehicle-mix percentages discussed earlier. The final matrices of zone-to-zone modal energy consumption for all trips can now be aggregated into district-to-district flows. These matrices (before or after aggregation) can also be added together to equal energy consumed by complete origin to destination trips. This last result is directly comparable to the matrix of direct energy consumption for automobile trips.

DIRECT ENERGY ACCOUNTS FOR THE CHICAGO SCA

The Chicago SCA covers the eight-county northeastern Illinois-northwestern Indiana metropolitan area. This region is divided into approximately 1800 zones that range from 0.65 km^2 (0.25 $mile^2$) in downtown Chicago to 23.3 km^2 (9 $miles^2$) in rural portions of outlying counties. Although all calculations are carried out at the zonal level, the results are aggregated into 64 larger districts to facilitate their presentation. These districts result from the intersecting areas of circumferential rings and radial corridors that extend from the Chicago central business district (CBD).

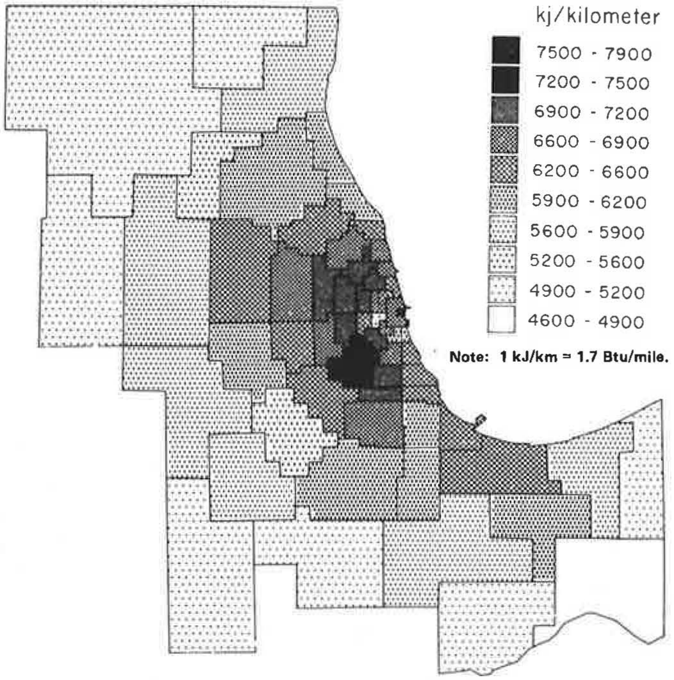
Table 1 presents a summary of the energy accounts for the entire region. Note that direct energy consumption for private travel is 18 times larger than that for public travel but that the number of person trips by automobile is only 6 times as large. Thus, an average automobile trip consumes 3 times the energy of an average public transit trip, including access by automobile or bus. This difference occurs despite the fact that the average automobile trip is 30 percent shorter than the average public transit trip. By comparing actual kilometers traveled to air kilometers (straight-line distances), these figures also show that the public transit trips are not longer because of circuity. The circuity of automobile trips is actually greater. This nonintuitive result occurs for the Chicago SCA because transit trips are heavily focused on the CBD, which is serviced by radial rail transit that permits direct trips. More than 55 percent of the total person kilometers traveled by public transit modes in this region are by rail rapid transit or commuter rail. One other observation to be made from Table 1 is that electrical energy, which can be produced from nonpetroleum resources, equals 37 percent of the public travel energy but only 2 percent of the public plus private energy.

These regional totals are obtained by aggregating results that were performed at the zonal level. The aggregation of these results into districts are shown as maps in Figures 6 and 7. The limited length of this paper does not allow a full display of maps, but the two shown here reveal an expected observation: Direct energy per person air kilometer increases toward the CBD for automobile trips because of greater traffic congestion. On the other hand, direct energy per person air kilometer decreases toward the CBD for public travel because of higher patronage and less use of automobile access. Note that these maps are for all public or private trips that originate from each origin and not just trips that have CBD destinations. That these maps are almost negatives of each other suggests that shifting more CBD-oriented trips with suburban origins to public modes represents a possible energy-reduction strategy for the Chicago region.

ACKNOWLEDGMENT

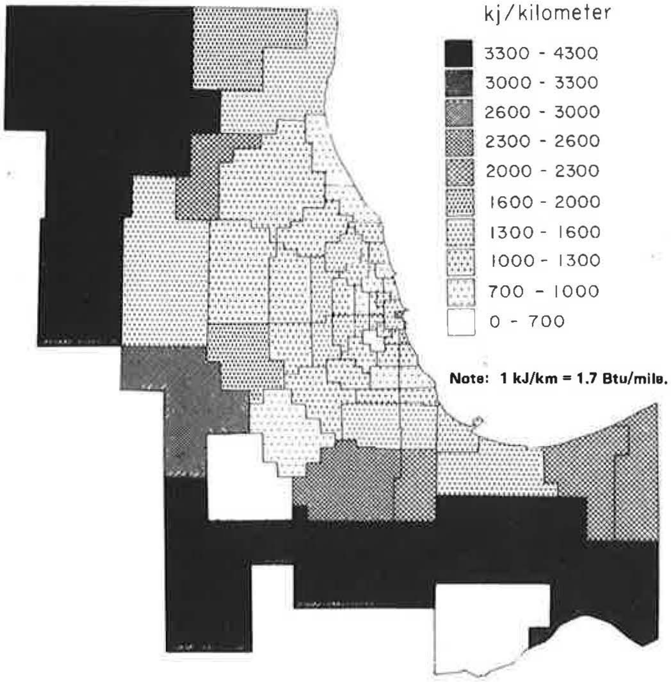
The research for this paper was supported by a contract with the Urban Mass Transportation Administra-

Figure 6. Peak-period private transportation by origin district (kJ/person air-km).



Note: 1 kJ/km = 1.7 Btu/mile.

Figure 7. Peak-period public transportation by origin district (kJ/person air-km).



Note: 1 kJ/km = 1.7 Btu/mile.

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